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4. Title of the invention: Detector Devices

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Detector Devices

This invention relates to detector devices, their use in detecting neutrons and to methods for detecting neutrons, with particular, but by no means exclusive, reference to fast neutrons of energy greater than 5.0MeV.

Neutrons interact with the nucleus of an atom. Unlike X-rays, which interact with the electrons of an atom and thus are sensitive to the density of a material, neutrons are able to penetrate high density materials. This is a result of the nature of the interaction and of the low neutron scattering cross sections associated with high density materials. In contrast to X-rays, low density materials are more opaque to neutrons.

Thermal neutron radiography is currently routinely used as a non destructive testing and imaging method with many end applications. In contrast, fast neutron radiography is not a commonly used technique. This is despite numerous potential attractions to the use of fast neutron radiography. These attractions include the non destructive nature of the method, the penetrability of fast neutrons through high density materials, and the possibility of element sensitive imaging through resonance radiography (if the neutron energy matches a resonance corresponding to a specific element, the neutron flux scattered by that element will be relatively greater than that produced by the surrounding medium, thus enhancing the contrast of that element relative to the background). A further consequence of the high penetrating power of high energy neutrons is that large objects can be probed. There are a variety of industrial applications which fast neutron radiography might be employed in, such as contraband, narcotics and explosives detection, and cargo inspection.

Commonly used position sensitive detectors for fast neutron radiography utilise charge coupled devices (CCDs) and scintillators as imaging tools. There are problems associated with both of these detection elements. The most widely used methods for fast neutron detection currently depend on the elastic scattering of protons and the subsequent conversion of the proton energy into a number of electrons. In turn these are often converted into light be means of a scintillator material. Transduction of this light into an electrical signal is accomplished using a CCD.

The cross-section for the scattering of protons is very much lower than that for the absorption reactions $^{7}Li(n,\alpha)$ or $^{10}B(n,\alpha)$ which are used for detection in thermal neutron radiography (see below). The total cross-section for neutron scattering in hydrogen as a function of energy drops rapidly with energy from about 11 barns at 150 keV to about 1 barn at 10 MeV. In spite of this it is larger than the cross-section for most other reactions that could be considered.

The primary efficiency of the scintillator detector can be defined as the ratio of the total number of neutrons that interact with the screen, to the number of neutrons that are incident on it. Defined in this way the primary efficiency ε_p is:

$$\varepsilon_p = (1 - \exp^{N\sigma d})$$

where N is the density of the hydrogen atoms, σ is the cross section and d is the thickness of the screen. Figure 1 shows the efficiency of a screen as a function of its thickness for a number of common hydrogen containing materials at a cross-section of 1.1 barns for 8 MeV neutrons.

In the case of a converter in the form of a slab, the maximum thickness is limited by the range of spreading of light within the screen and its effect on the resolution

and the transparency of the detector to its own light. Polyethylene, which has two hydrogen atoms for each carbon atom, is the most efficient, but it has the disadvantage of not being transparent when a scintillator is used (although it is translucent). Polypropylene is transparent although its primary efficiency is some 17% lower than for polyethylene.

A particularly effective form of scintillator is a block of polypropylene containing ZnS as the scintillator. ZnS has several advantages including a very high light output for heavy charged particles, such as protons, and a low sensitivity for electrons. This detector is commercially available as the "PP Converter". This converter is opaque to its own light and its thickness is limited to 2mm with an efficiency of about 2%. All thick scintillators suffer from the problem of light spreading due to scattering within the body of the converter.

Thus, the efficiency of hydrogen rich scintillators exploiting the proton recoil reaction to indirectly detect the neutrons are limited by their concentration of hydrogen and neutron scattering cross section. Furthermore, the light conversion step limits the thickness of the scintillators, which in turn influences light spreading, light scattering and image blurring.

There are further disadvantages associated with the use of CCDs. The physical limitation imposed by the sizes of the CCDs implies that complex optical systems involving lenses and optical fibre tapers are required to image areas that are larger than 8.6cm x 11.05cm, which is the size of the largest optical CCD produced. Using optics in the imaging process reduces the light collection efficiency of the imaging system. Often, image intensifiers have to be used to boost the photon signal emerging from the optics of the detector system. Since crystalline silicon is prone to radiation damage, the CCD is often placed outside of the primary neutron beam. As a result, the light from the

scintillator has to be reflected through the optics of the camera by suitable mirror. The use of a lens represents another component in the optical system which results in further light losses.

Ambrosi *et al* (R.M. Ambrosi, J.I.W. Watterson and H. Rahmanian, Proc. SPIE 4142 (2000) 331) describe fast neutron radiography using scintillators in combination with i) CCDs and ii) an amorphous silicon (a-Si) sensor array. Although the amorphous silicon sensor array does not suffer from some of the disadvantages associated with CCDs, the above described problems with the use of scintillators remain. The contents of Ambrosi *et al* are herein incorporated by reference.

As noted above, thermal neutron radiography is used currently as a non destructive testing and imaging method. Of particular relevance to the present invention is the recent demonstration that microchannel plate (MCP) detectors are capable of imaging cold and thermal neutrons (W.B. Feller, R.G. Downing, and P.L. White, "Neutron Field Imaging with Microchannel Plates", Proc SPIE 4141 (2000) 291, and R.G. Downing *et al.*, "High Resolution Imaging of Low-Energy Neutrons with Microchannel Plates", Trans. Amer. Nucl. Soc., 82 (2000) 83). The key to the detection process is the use of specially prepared, boron enriched MCPs, an approach that was originally predicted by Fraser and Pearson at the University of Leicester (G.W. Fraser and J.F. Pearson, "The Direct Detection of Thermal Neutrons by Imaging Microchannel Plate Detectors", Nucl. Instr. Meth., A293 (199) 569).

To register an MCP output charge with a high degree of spatial resolution, a number of current MCP based imaging systems are known which include scintillator screen systems and compatible pulse counting electronic readouts. The latter type of system has not been utilised for neutron detection with MCPs. The electronic readout systems can be categorised into two classes:

(1) Discrete wire anodes, which digitise event positions based on wire group selection (MAMA, cross grid charge detector, codacon).

(2) Contiguous centroid position encoders (eg, resistive anode encoder (RAE), delay line, wedge and strip, etc.), which digitise x-y coordinates in the associated electronics.

Discrete wire readout type anodes suffer from a number of disadvantages, such as limited size, Moire effects, and image undersampling. Centroiding readouts overcome these disadvantages and offer large format high resolution MCP imaging systems. Crucially, however, neither readout class offers the key combination of very large formats for radiography at reasonable cost.

From the foregoing, it will be apparent that there is a need for an improved detection system for neutrons, particularly fast neutrons (of energy greater than 5 MeV), and even more particularly for an imaging system for fast neutrons. More specifically, there is a need for position-sensitive neutron detectors that have a combination of high sensitivity, high spatial resolution or imaging power, whilst simultaneously minimising interference from low energy scattered neutrons and background radiation such as gamma rays. Furthermore, there is a need for improved MCP detector devices which are capable of a high degree of spatial resolution. Such detector devices would not be limited to the detection of neutrons *per se*.

The present invention overcomes the aforementioned problems and disadvantages of the prior art, and satisfies the above described needs.

According to a first aspect of the invention, there is provided a method of detecting fast neutrons of energy greater than 5MeV comprising the steps of:

providing a neutron detector comprising a microchannel plate detector directly coupled to an electron detector without an intermediate scintillator layer;

positioning the microchannel plate detector so that neutrons are incident on said microchannel plate detector; and

detecting the output of the electron detector.

In this way, the aforementioned problems and disadvantages are overcome, and the aforementioned needs are satisfied. The present invention offers numerous advantages, such as high sensitivity, submillimetre resolution, minimal interference from low energy scattered neutrons (which would cause blurring), and minimal interference from background radiation such as gamma rays. Additionally, the detector device used to detect neutrons has the advantage of being radiation hard. Additionally still, the present invention enables large format detectors to be used conveniently for neutron detection. In contrast to prior art techniques which utilise scintillators, the present invention does not utilise a light conversion step, and hence resolution and contrast are not affected by light spreading and light scattering. Fast neutrons of energy greater than 5 MeV are detected. By doing so, the present invention can take advantage of the high penetrability of such neutrons. The present invention provides an understanding of the physical mechanisms involved in enabling MCPs to detect neutrons of such high energy, and exploits these physical mechanisms. In particular, the present invention exploits neutron interaction with elemental silicon in the MCP. It is advantageous that silicon can be used as the active element for the detection of fast neutrons, since silicon is inherently present in conventional MCP structures. This can be contrasted with the boron enriched MCPs utilised to detect thermal neutrons: boron is not a constituent of conventional MCPs, and therefore special procedures and additional expense are required to introduce it into MCPs.

The area of the microchannel plate detector upon which the detected neutrons are incident may be greater than $1.0 \times 10^{-2}m^2$, preferably greater than $5.0 \times 10^{-2}m^2$, most preferably greater than $5.0 \times 10^{-1}m^2$.

Preferably, the electron detector is without an entrance window, thereby permitting direct accumulation of electron charge from the microchannel plate detector on the electron detector.

The electron detector may comprise a pixel array detector. The electron detector may comprise an amorphous silicon or an amorphous selenium pixel array detector. Such detectors are position sensitive, and are particularly well suited to use with MCPs, and exhibit low noise levels. Additionally, these detectors are available in large formats at reasonable cost, and are well suited to imaging applications.

The microchannel plate detector may comprise greater than 45% by weight of silicon, preferably greater than 90%. By enhancing the amount of silicon present, the neutron detection efficiency is enhanced. Another way of enhancing neutron detection efficiency is to provide MCPs of relatively large thickness. MCP thicknesses of greater than 5mm, or even greater than 10mm, may be used.

In a preferred embodiment neutrons are imaged by the method, in which instance the step of detecting the output of the electron detector comprises assembling outputs from different discrete areas of the electron detector in order to produce an image of neutrons incident on said microchannel plate detector. In this way, a number of imaging applications, such as cargo inspection and contraband, narcotics and explosives detection, may be realised. Imaging of fast neutrons is particularly preferred.

The microchanel plate detector may comprise an array of individual microchanel plate devices. The array may comprise a stacking of MCPs (in order to increase the overall thickness of the MCP stage) and/or a tile of MCPs (in order to provide a detector having a MCP stage of increased surface area).

According to a second aspect of the invention there is provided a detection device for detecting radiation such as neutrons and X-rays comprising a microchanel plate detector directly coupled to a pixel array electron detector, in which the microchannel plate detector is directly coupled to the electron detector without an intermediate scintillator layer. In addition to detecting (and imaging) neutrons, such devices can be used in X-ray imaging and neutron focusing applications.

The electron detector may be an amorphous silicon or amorphous selenium pixel array detector.

The electron detector may be without an entrance window thereby permitting direct accumulation of electron charge from the microchannel plate detector on the electron detector.

The microchannel plate detector may have a front face upon which radiation is incident, and the surface area of said front face may be greater than $1.0 \times 10^{-2} m^2$, preferably greater than $5 \times 10^{-2} m^2$, most preferably greater than $5.0 \times 10^{-1} m^2$.

The device may image radiation (such as neutrons and X-rays), the device further comprising imaging means for assembling outputs from different discrete areas of the electron detector in order to produce an image of radiation incident on said microchannel plate detector.

According to a third aspect of the invention there is provided the use of a device according to the second aspect of the invention to image neutrons.

Fast neutrons of energy greater than 5MeV may be imaged.

According to a fourth aspect of the invention there is provided the use of a device comprising a microchannel plate detector directly coupled to an electron detector without an intermediate scintillator layer to image fast neutrons of energy greater than 5MeV.

Devices, methods and uses in accordance with the invention will now be described with reference to the accompanying drawings, in which:-

Figure 1 shows a) a perspective view and b) a cross sectional view of a device according to the invention;

Figure 2 shows primary efficiency for neutron detection for candidate materials for neutron screens in fast neutron radiography, calculated for 8 MeV neutrons (total cross section 1.1 barns) as a function of the converter thickness;

Figure 3 shows reaction cross section as a function of neutron energy for $^{28}Si(n,p)^{28}Al$, $^{28}Si(n,\alpha)^{25}Mg$, $^{28}Si(n,d)^{27}Al$ and $^{28}Si(n,np)^{27}Al$ conversion reactions in a hypothetical silicon based MCP detector;

Figure 4 shows a conventional alkali lead silicate glass MCP structure with 5μm round pores;

Figure 5 is a schematic diagram of a MCNP model used in Example 1;

Figure 6 shows neutron detection efficiency as a function of MCP thickness and composition;

Figure 7 shows the point scattering function for a 10mm thick MCP composed of standard MCP glass and containing 20% Si;

Figure 8 shows the point scattering function for a 10mm thick polypropylene radiator;

Figure 9 shows the point scattering function for a 10mm thick MCP composed of 90% Si and 5% H; and

Figure 10 shows background generated by photons in comparison to the primary neutron signal.

Figure 2 shows a device 10 of the present invention. The device 10 comprises a MCP 12 disposed in a vacuum vessel 14. One end of the vacuum vessel 14 is sealed via an O-ring 16 to an electron detector, such as an amorphous silicon (a-Si) readout array 18. There is no scintillator layer intermediate the MCP 12 and readout array 18, and thus a direct coupling is established, without a light conversion step. The vacuum vessel 14 is sealed to the glass substrate of the amorphous silicon readout array 18. The anode of the readout array 18 is in connection with a support substrate 20. A bonding agent such as an epoxy resin may be used to effect this connection. Electrical contacts 22 are provided, which enable the output of the readout array 18 to be measured, and appropriate voltages to be applied to the MCP 12 and readout array 18. The vacuum vessel 14 is in connection with a vacuum tube 24, which has a vacuum flange 24a permitting

connection of the device 10 to a vacuum system (not shown). The vacuum system can house a source of neutrons, and/or be used to transmit neutrons from a neutron source to the detector device 10. Additionally, the vacuum system might house an object which is to be imaged by the device 10. It will be apparent to those skilled in the art that there are numerous ways in which the neutron source and an object to be imaged might be disposed with respect to the device 10.

An appealing aspect of the present invention is the use of a MCP. One advantage is that MCPs provide an amplification effect due to the electron avalanche which is created in the microchannels during detection. Another advantage is that MCPs offer the possibility of high spatial resolution - limited, essentially, by the size of the microchannels. However, it must be emphasised that these potential benefits can only be realised if the MCP is suitably coupled to an appropriate detection system which is capable of detecting electrons produced by the MCP without significantly degrading performance.

The neutron detection system provided by the present invention employs a MCP detector as the neutron converter and an electron detector as the readout for the microchannel plate converter. Interactions between the neutrons and certain elements in the MCP (described in more detail below) are used in the neutron detection process in the microchannel plate converter. The nuclear interactions produce charged particles which ionise the MCP material and generate electrons which in turn interact with the walls of the channels in the MCP. A potential applied across the MCP results in the multiplication of the charge generated by the initial neutron interaction. The total charge output of each channel is read out by the electron detector. The imaging process does not require a light conversion step, a characteristic of current scintillator based fast neutron imaging methods, and hence the resolution and contrast of the imaging process is not affected by light spreading and light scattering.

A further advantage of the present invention is that the use of large format detection systems is readily accommodated: indeed, such large format systems are preferred embodiments of the present invention, since imaging of relatively large objects can be accomplished without the disadvantage encountered with the scintillator-CCD prior art detection systems of having to employ image reduction optics. It is preferred that the area of the MCP (or the combined area of the MCPs if more than one MCP is used in the "front face" of the detector) is greater than $1.0 \times 10^{-2}m^2$, more preferably greater than $5.0 \times 10^{-2}m^2$, and most preferably greater than $5.0 \times 10^{-1}m^2$. In fact, MCP areas as large as $1m^2$ or greater might be used. The active area of the electron detector would, of course, generally be commensurate with the area of the MCP. Thus, it is preferred that the electron detector has an electron detecting face of surface area greater than $1.0 \times 10^{-2}m^2$, more preferably greater than $5.0 \times 10^{-2}m^2$, most preferably greater than $5.0 \times 10^{-1}m^2$.

A preferred form of electron detector is a pixel array detector. Such detectors possess an array of pixel diode detectors, each pixel having readout electronics. Such detectors are readily available in large format form and exhibit low noise. A particularly preferred form of pixel array detectors comprise amorphous semiconductor devices, such as amorphous silicon or amorphous selenium detectors. Amorphous silicon pixel array detectors are in active commercial production (for example, by Varian Imaging Products, Palo Alto, California, USA) for medical radiography, high energy physics and other fields, although the combination of such devices with MCPs as proposed herein has not previously been described. Typically, a matrix of, for example, 127 x 127μm square and 30 micron thick diodes is read out by an array of thin-film transistors. Another feature of the present invention is the approach employed to digitally read out the potentially large format MCPs. This approach employs large area, low noise amorphous silicon imaging arrays. These arrays are typically fabricated in the form of rows of individual photodiode sites attached to a common readout line per row. The individual pixels are switched onto the readout line through rows of thin film transistors which are gated via common

columnar contacts. The result is an array of charge sites each with its own individual readout path to an external amplifier and digitiser. Further details of amorphous silicon pixel arrays can be found in Ambrosi *et al*, ibid. Large arrays (eg, 200mm x 250mm) of this basic design are increasingly available for commercial markets such as medical radiography. In operation, charge pulses emitted from the MCP output accumulate on the diodes, and subsequently would be read out as described above. The spatial resolution of current amorphous silicon detectors only is slightly inferior to the spatial resolution theoretically possible with standard MCPs, and so a slight degradation in spatial resolution may be expected. Amorphous silicon detectors having smaller pixel sizes are currently under development, and it is likely that such devices will become available in the future. The use of such devices would result in further improvement in spatial resolution. It should be noted that detector devices such as amorphous silicon detectors usually possess an entrance window which, in the present invention, incident electrons from the MCP must penetrate, thereby degrading gain somewhat. It is preferred that the electron detector is coupled to the MCP without an intermediate entrance window. In this way, electron charge from the MCP directly accumulates on the electron detector. In the case of the amorphous silicon detector, electron charge accumulates on the plates of the diodes.

An important aspect of the present invention is the detection and imaging of fast neutrons, ie, neutrons of energy greater than 5.0 MeV. The present invention exploits an understanding of the fundamental physics of the interaction of fast neutrons with materials. As discussed previously, cold and thermal neutrons (of energy less than 1eV) can be detected using specially boron enriched MCPs. The present invention recognises that elemental silicon (already present in conventional MCP alkali lead silicate glass) can be used as the active neutron converter for fast neutrons, by way of exploiting the $^{28}Si(n,p)^{28}Al$, $^{28}Si(n,\alpha)^{25}Mg$, $^{28}Si(n,d)^{27}Al$ and $^{28}Si(n,np)^{27}Al$ conversion reactions. These reactions result in the production of an electron pulse within the MCP structure.

Figure 3 shows cross sections for the $^{28}Si(n,p)^{28}Al$, $^{28}Si(n,\alpha)^{25}Mg$, $^{28}Si(n,d)^{27}Al$ and $^{28}Si(n,np)^{27}Al$ reactions as a function of neutron energy. At neutron energies between 5 and 10 MeV, the first two of these reactions are exploited. The highest combined cross section is observed at ca. 8 MeV. The (n,d) reaction only becomes effective at energies above ca. 10 MeV, and the (n,np) reaction only becomes effective above ca. 12 MeV. The energy thresholds in the cross sections of these reactions indicate that an appropriate MCP detector would provide the neutron energy discrimination necessary to reduce the effect of low energy neutron scatter on the detectability of small features in fast neutron radiography applications. Reduced neutron scattering results in improved image contrast and resolution.

It should be noted that the $^{28}Si(n,p)^{28}A1$, $^{28}Si(n,\alpha)^{25}Mg$, $^{28}Si(n,np)^{27}Al$ and $^{28}Si(n,d)^{27}Al$ conversion reactions are not the only reactions contributing to the neutron reactions of the lead silicate MCP glass. There will also be (n,p) and (n,α) reactions with the alkali metal constituents of the glass, minor neutron reactions with the Pb and O nuclei present in the glass, with thresholds in these cases being above 2.5 MeV, and with ^{39}K which has a cross section of 0.2 barns above 1 MeV. These reactions further contribute to the neutron detection ability of MCPs in standard lead glass MCPs.

Figure 4 shows the structure of a typical MCP optic used in X-ray applications. The structure comprises a wall structure 40 which defines a "honeycomb" of microchannels 42. The structure of the MCP and nature of the reaction imply that the signal from the neutron detection process will be confined to the channels of the MCP; therefore, the intrinsic resolution of the converter screen is limited by the dimensions of the MCP channels. An industry standard for glass MCP structures comprises a 15μm channel pitch and 12μm channel diameter. Therefore, the channel wall thickness is of the order of a few microns. The thickness of these plates is of the order of a few millimetres. The maximum etchable thickness of glass is of the order of 10μm. In current lead silicate

glass MCPs, the silicon content is typically ca. 18% Si by weight in SiO_2. It is likely that, in order to detect fast neutrons with good sensitivity, the silicon content of the MCP is improved somewhat in comparison to conventional lead silicate glass MCPs of the type described above. There are a number of ways in which this can be accomplished: these strategies are discussed below.

In one strategy the proportion by weight of the MCP which is comprised of Si is increased with respect to conventional lead silicate glass MCPs. It is believed that increases of up to 50% Si in SiO_2 can be obtained readily. Furthermore, "all silicon" MCP devices are under development (by NOVA Scientific Inc., Sturbridge, MA, USA and Nanosciences Corp., Oxford, CT, USA). Such devices, and methods for manufacturing same, are disclosed in US 5,997,713, US 6,045,677, US 6,384,519 and O.H.W.Siegmund, A.S. Tremsin, J.V. Vallerga, C.P. Beetz, R.W. Boerstler, J. Yang and D. Winn, in X-Ray and Gamma-Ray Instrumentation for Astronomy XII, Proceedings of SPIE, 4497 (2002) 139, the contents of all of which are herein incorporated by reference.

In another strategy, the thickness of the MCP is enhanced. The thickness of the walls of the MCP and/or the thickness of the MCP itself might be increased. One way in which overall thickness might be increased is to use a stacking of two or more individual MCPs to provide a thick stacked structure. As noted previously, the use of a plurality of MCPs to form the front face of the detector is within the scope of the invention. It is possible to combine these two approaches by utilising a three dimensional array of MCPs, ie, a configuration in which stacking of MCPs is used to increase the detector thickness and to increase the area of the front face of the detector.

Since there is no light conversion step and neutron scattering is not an issue, the thickness of the detectors are limited only by the concentration of silicon and the linear attenuation coefficient of the material used in the MCP. It is possible to increase the

channel diameter to facilitate the channel etching process as an alternative to standard MCP manufacturing techniques. The ratio of the channel wall thickness to the channel diameter depends strongly on manufacturing limitations. It should be noted in this regard that in the case of an amorphous silicon or selenium photodiode array, the intrinsic resolution of the detector would be limited by the pixel size of this array (~100μm). Thus, it is possible to utilise a MCP channel diameter which is of the order of the dimensions of a readout pixel without affecting the spatial resolution of the device. The use of larger channel diameters may facilitate the manufacturing process.

Example 1

Detector efficiency was modelled as a function of detector composition and thickness using Monte Carlo techniques.

Four MCP compositions were investigated:

1. standard MCP glass containing ~20% silicon by weight.
2. silicon dioxide MCP composed of 45% silicon.
3. all silicon MCP with 90% silicon.
4. 90% silicon MCP with 5% additional hydrogen.

In the first case, the primary component of the MCP glass was lead (50%) with additional components being oxygen (25%) and potassium (5%). All reactions between neutrons and the components of the MCP were considered including reactions producing gamma rays. The products of these reactions were examined to determine how the gamma ray background would interfere with the primary neutron detection process of the silicon components of the MCP glass.

In the second and third cases the only reactions considered were those with the silicon component of the MCP glass.

In the last case the hydrogen was added in order to determine how a small quantity of hydrogen would improve the neutron detection efficiency by exploiting the proton recoil reaction that is used in common fast neutron scintillating converter screens.

Modelling the MCP Structure

The first past of the model was based on the assumption that if each element of the a-Si array is approximately 100μm x 100μm in area and there is one MCP channel for each a-Si pixel, then each channel could have a 75μm diameter and a 25μm total wall thickness. The hypothetical MCNP geometry used in this part of the study is depicted in Figure 5. In this model the MCP channels 50 were assumed to be cylindrical; however, MCPs with channels of a different shape, such as square or hexagonal, could also be considered. The channel wall 52 thickness to diameter ratio could also be varied in order to further optimise the MCP configuration.

Modelling the Point Scattering Function of the Detector Material

The second part of the model required exploring the point scattering function for the materials in question. This technique was used to determine how the threshold in the silicon-based reaction used to detect the neutrons reduces the neutron scatter component in the detector. This affects the detectability of the feature of interest in a radiograph.

The point scattering function for the converter screen material was evaluated using a cylindrical geometry. A line source of neutrons was directed down the axis of a hypothetical silicon-based cylinder and the tallies were collected in a series of annular concentric volumes with a varying pitch ranging from 0.0125mm, close to the centre of the converter screen, to 20mm close to the edge of the converter screen. On this basis, a point scattering function was evaluated. This is the point scattering function for the detector and not, as is more usual, for the specimen. The Monte Carlo code MCNP-X was used to determine the number of neutron interactions with the silicon component of the MCP glass as a function of Si concentration, converter screen thickness and neutron energy.

Results of the Computational Model

Detector Efficiency

The neutron detection efficiency of the MCP converter screens were evaluated as a function of composition and thickness. The results of the MCNP model are shown in Figure 6. From the results it can be seen that increasing the Si concentration increases the overall efficiency of the detector. From the results it is also evident that increasing the MCP thickness beyond 30mm does not increase the efficiency significantly. The addition of small quantities of hydrogen also has the effect of increasing the overall

efficiency by exploiting both the proton recoil reaction and the reactions with the silicon component.

Neutron Scatter

The point scattering function method described previously was used to determine how the threshold in the silicon reaction results in a reduction in the low energy scatter component associated with plastic scintillators. The results of the point scattering function model are shown in Figure 7. A direct comparison between these results and those associated with plastic scintillators can be made by examining the differences between Figures 7 and 8. Figure 8 depicts the result obtained by repeating the Monte Carlo simulation by substituting the MCP material with a plastic radiator associated with fast neutron scintillators. Figure 9 highlights the effect that the addition of small quantities of hydrogen has on the scattered low energy background.

Background

A comparison was made between the number of primary neutron interactions in the MCP and the number of photons produced by these neutrons interacting with the MCP structure. As evidenced in Figure 10, in all cases the photon interactions were at least two orders of magnitude lower than the primary neutron interactions.

Example 2

A series of calculations were performed to estimate the signal to noise values associated with the MCP a-Si detector combination for a typical 8MeV neutron flux from an accelerator based source. The accelerator based neutron source comprised a 5MeV, 20μA, deuteron beam interacting with a deuterium gas target at atmospheric pressure. The

neutron flux at the detector (situated at ~30cm from the deuterium gas cell) was calculated to be 1×10^7 neutrons $cm^{-2} s^{-1}$. The a-Si detector pixel size was 127µm x 127µm. Thus the neutron flux was 1.6×10^3 neutrons $pixel^{-1}s^{-1}$ or 1.0×10^3 neutrons s^{-1} over a 100µm x 100µm area of the MCP structure used in this model. If the scintillating converter screen was replaced with a 30mm or 50mm thick MCP, the neutron detection efficiency would vary between 2% and 12% depending on the silicon and hydrogen concentration. If the assumption is made that one detected neutron produces at least one electron at the channel wall, the total number of electrons collected by the a-Si diode can be evaluated. Although the sensitive area of each 127µm x 127µm pixel covers only 56% of the pixel (~71µm) and each channel in the MCP model has a diameter of 75µm. Therefore, this specific model one channel per pixel is a fair assumption. Since the total rms noise associated with a-Si pixel arrays is currently ~800 electrons rms, the signal to noise ratio (S/N) per detector pixel can be estimated for an average MCP gain per channel. Neutrons can interact anywhere within the MCP structure. Those electrons produced near the MCP front face would benefit from the maximum gain voltage between the MCP and the a-Si array. Conversely, electrons provided from interactions close to the back end of the MCP would result in a minimum gain. If the maximum gain were of the order of 10^4 volts, a simple Monte Carlo sampling method can be used to determine what the average signal in electrons per pixel will be. For neutrons interacting in the bulk of the MCP material the interaction probability density function (pdf) is given by

$$pdf(x) = \mu exp(-\mu x)$$

where x is the interaction depth in the detector and µ the linear attenuation coefficient of the material. The cumulative probability distribution function (cpdf) is given by:

$$cpdf = 1 - exp(-\mu x) \qquad (1)$$

If it is assumed that one electron reaches the MCP channel wall per interacting neutron then for a given MCP peak gain (~10^4) the signal reaching the pixel of the a-Si array can be evaluated by sampling equation (1) and multiplying by a corresponding gain value. This method can be used to generate a sample of signal values and the average signal as a function of the MCP detector thickness and silicon content can be evaluated. Tables 1 and 2 summarise the results of these calculations for both 30mm and 50mm thick MCP converters.

Table 1. Estimated S/N for a 30mm thick MCP structure.

Silicon Content	Neutron Detection Efficiency	Detected Neutrons/pixel[a]	Average Signal Electrons/pixel[b]	S/N[c]
20% (Si)	2.2%	22	$1.6 \times 10^4 \pm 3.2\%$	20
45% (Si)	2.3%	23	$4.4 \times 10^4 \pm 2.5\%$	55
90% (Si)	5.6%	56	$8.5 \times 10^4 \pm 3.0\%$	106
90% (Si) + 5% (H)	10.6%	106	$1.0 \times 10^5 \pm 2.9\%$	130

[a] Given a flux of 1.0×10^3 neutrons s^{-1} over a 100μm x 100μm area of the MCP.

[b] Evaluated by Monte Carlo sampling methods.

[c] Given a 800 electron $pixel^{-1}$ rms noise level.

Table 2. Estimated S/N for a 50mm thick MCP structure.

Silicon Content	Neutron Detection Efficiency	Detected Neutrons/pixel[a]	Average Signal Electrons/pixel[b]	S/N[c]
20% (Si)	2.7%	27	$3.1 \times 10^4 \pm 2.5\%$	3.4
45% (Si)	2.9%	29	$6.8 \times 10^4 \pm 3.3\%$	3.6
90% (Si)	6.1%	61	$1.4 \times 10^5 \pm 2.8\%$	7.6
90% (Si) + 5% (H)	11.9%	119	$1.8 \times 10^5 \pm 2.7\%$	14.9

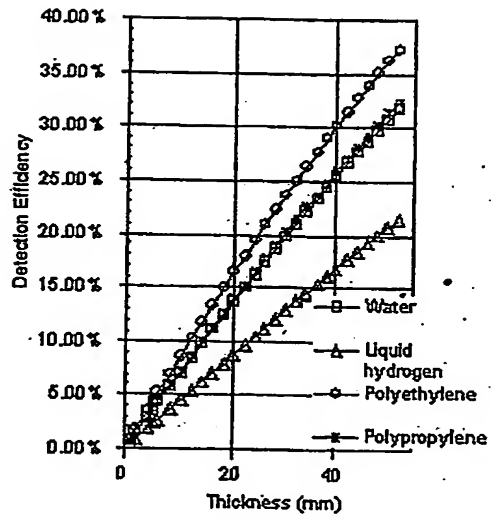
[a] Given a flux of 1.0 x 10^3 neutrons over a 100μm x 100μm area of the MCP.
[b] Evaluated by Monte Carlo sampling method.
[c] Given a 800 electron $pixel^{-1}$ rms noise level.

The signal to noise values shown above can be placed in context if compared to previous studies involving scintillating converter screens and both a-Si and CCD based detectors. In the study by Ambrosi *et al*, ibid the signal to noise obtained with a 2mm thick PP converter and an a-Si detector array was ~1.35 given 4000 electrons rms in total readout noise. Given the current noise levels associated with a-Si pixel arrays, ~800 electrons rms, the S/N would improve to a maximum value of 5.4; however, the problems associated with the low energy scattered neutron component and reduced spatial resolution caused by light scatter or spreading (in the case of thicker scintillators) remain. Image resolution values obtained with the a-Si/PP converter detector combination were of the order of a few millimetres. The MCP a-Si detector combination described in this Example would have an intrinsic resolution limited by the a-Si pixel size (~100μm).

Signal to noise values associated with the intensified CCD based detector system were higher, at least an order of magnitude higher than the values quoted in Tables 1 and 2. However, in comparison to the present invention, this detector has a number of problems associated with scintillator based detection methods and the limits imposed by the sized of CCDs. Imaging an area of approximately 11cm x 17cm with a CCD approximately 1.3cm x 0.8cm in size produced resolution values of at best 2mm with the PP converter. This is to be contrasted with the ~100μm resolution associated with the MCP/a-Si combination of this Example.

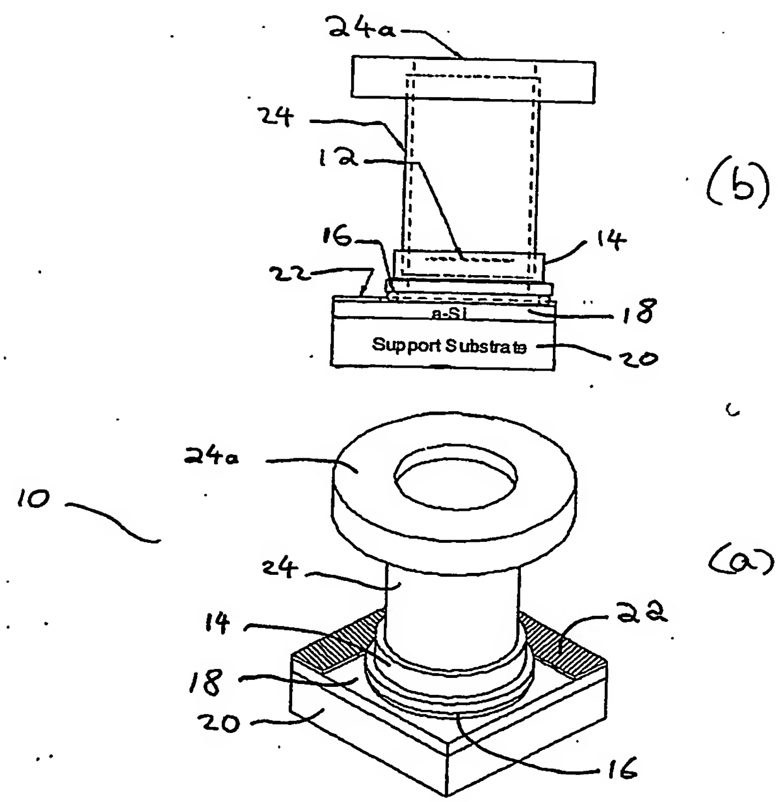
It will be apparent to the skilled reader that numerous modifications to the invention might be contemplated. For example, whilst fast neutron applications represent preferred aspects of the present invention, other forms of radiation, such as X-rays, might

be detected and imaged. Thermal neutrons might be imaged, in which instance a boron enriched MCP of the type previously described might be coupled to a suitable electron detector, such as an a-Si detector, without an intermediate scintillator layer.



40.00%
35.00%
30.00%
25.00%
20.00%
15.00%
10.00%
5.00%
0.00%
Detection Efficiency
0
20
40
Thickness (mm)
Water
Liquid hydrogen
Polyethylene
Polypropylene

Fig. 2



24a
24
12
16
22
14
a-Si
18
Support Substrate
20
(b)
24a
10
24
(a)
14
22
18
20
16

Fig. 1

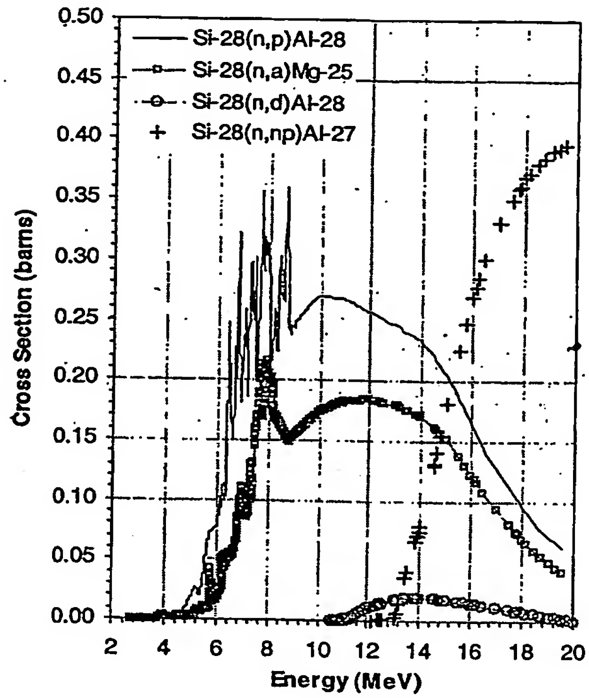
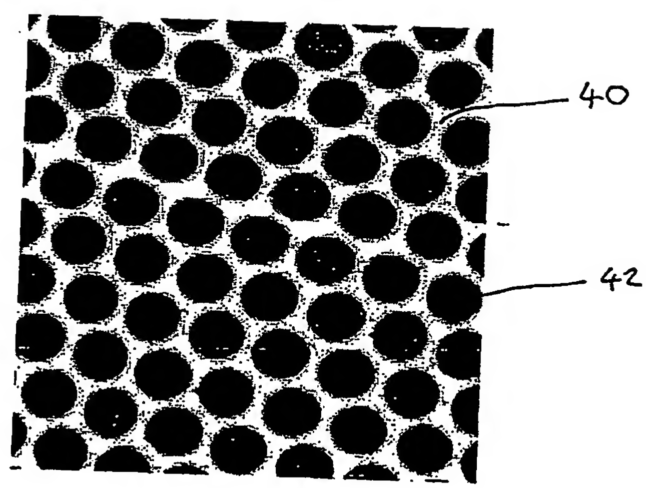


Fig. 3

Fig. 4



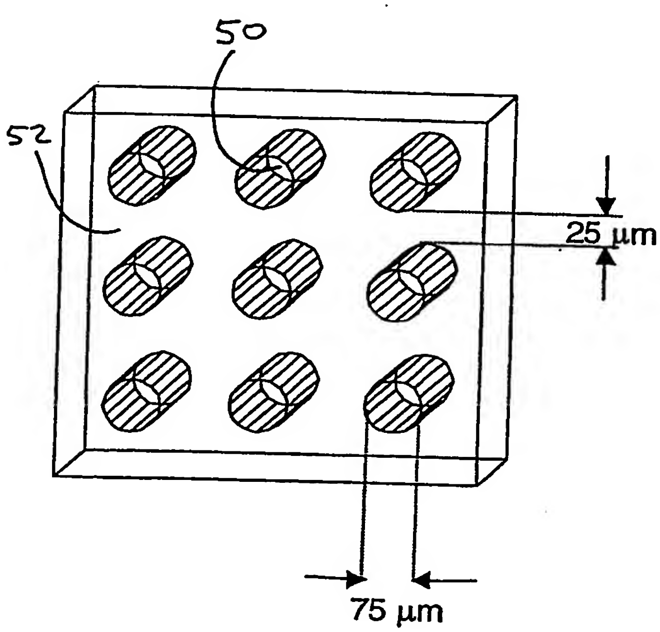
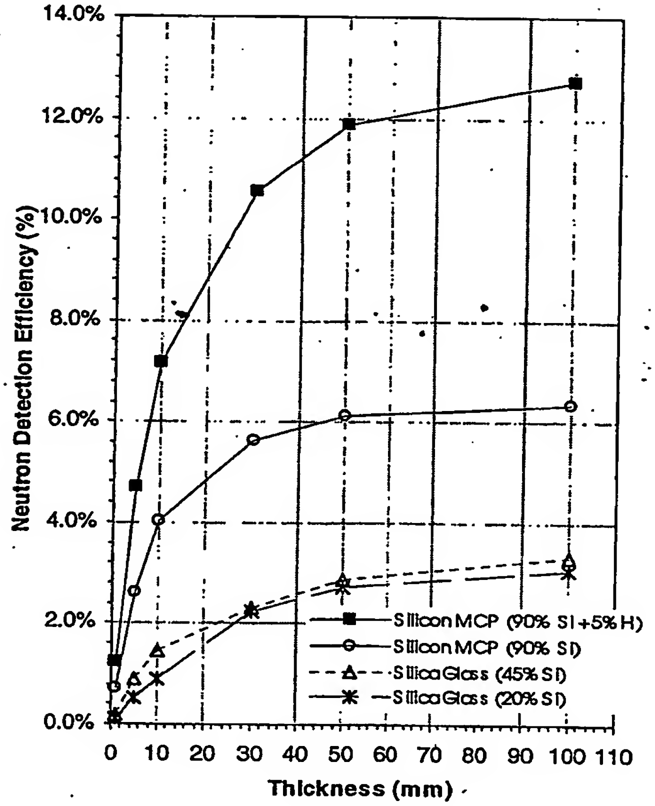
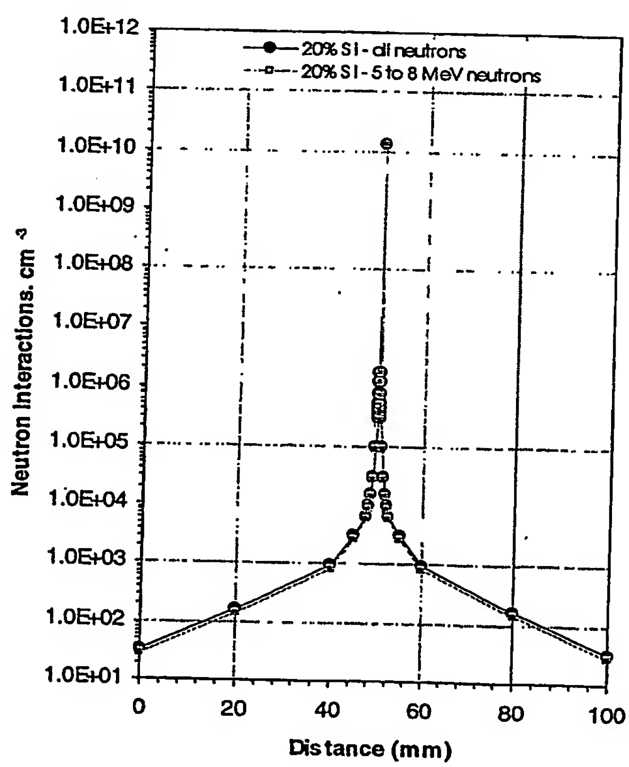


Fig. 5



14.0%
12.0%
10.0%
8.0%
6.0%
4.0%
2.0%
0.0%
Neutron Detection Efficiency (%)
Silicon MCP (90% Si + 5% H)
Silicon MCP (90% Si)
Silica Glass (45% Si)
Silica Glass (20% Si)
0 10 20 30 40 50 60 70 80 90 100 110
Thickness (mm)

Fig. 6



1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
Neutron Interactions. cm -3
20% Si - all neutrons
20% Si - 5 to 8 MeV neutrons
0 20 40 60 80 100
Distance (mm)

Fig. 7

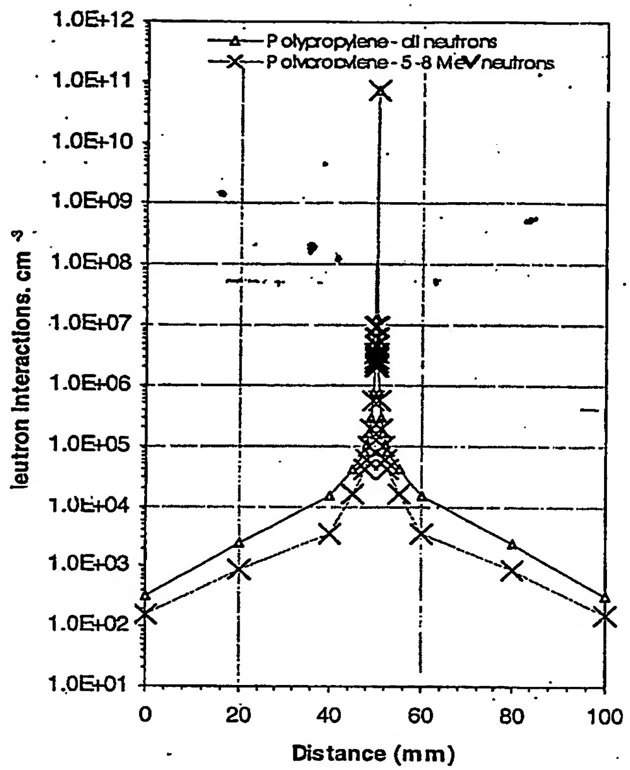
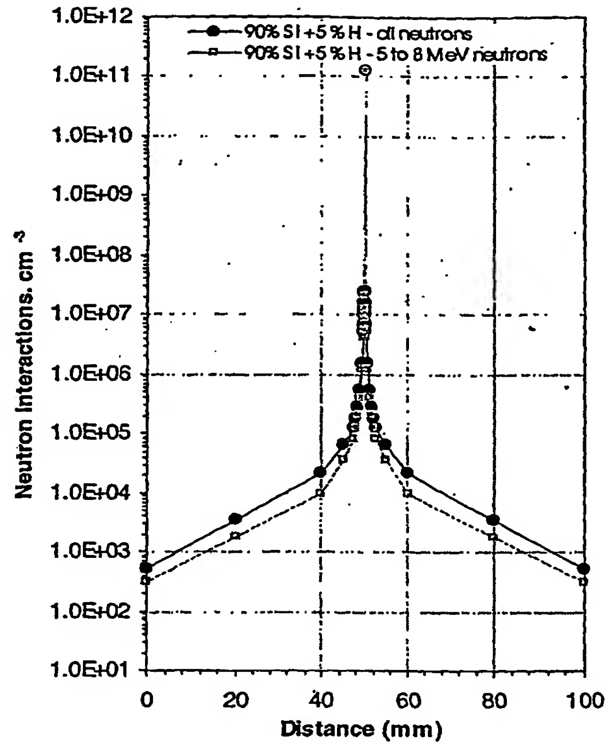
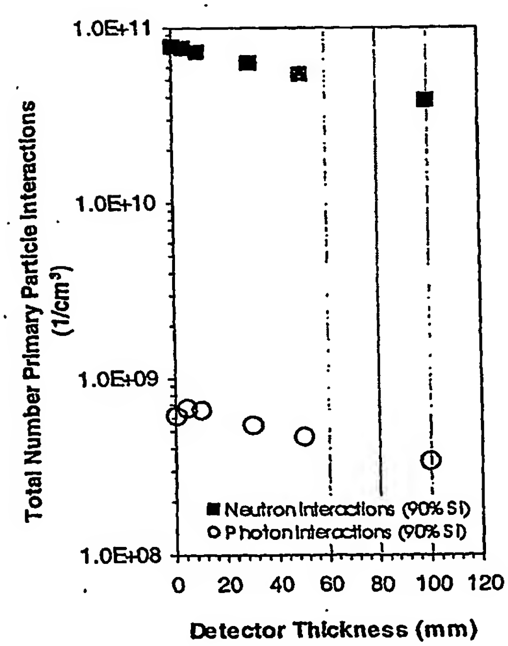

Polypropylene - all neutrons
Polypropylene - 5-8 MeV neutrons
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
leutron Interactions, cm -3
0
20
40
60
80
100
Distance (mm)

Fig. 8



90% SI +5 % H - all neutrons
90% SI +5 % H - 5 to 8 MeV neutrons
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
Neutron Interactions. cm -3
0
20
40
60
80
100
Distance (mm)

Fig. 9



1.0E+11
1.0E+10
1.0E+09
1.0E+08
Total Number Primary Particle Interactions (1/cm³)
Neutron Interactions (90% SI)
Photon Interactions (90% SI)
0
20
40
60
80
100
120
Detector Thickness (mm)

Fig. 10